Combustion enhancement in supersonic coaxial jet with an optimal forcing oscillations

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1 Introduction

The low combustion efficiency owing to the poor mixing performance is the main challenge in scramjet combustor. Rapid mixing is always required in the shear layer formed coaxial jet as the fuel injection [1]. However, the convective Mach number is large when main speed in the combustor is supersonic, which makes the growth rate of the mixing layer be suppressed [2]. Thus, the solely shear layer mixing of coaxial jet is not suitable for the supersonic combustion. Combustion enhancement strategies are needed to improve the combustion performance.

The effect of external excitation or forcing strategies on combustion performance is widely studied. The inlet velocity of coaxial jet is found to play the important role in affecting the flow structures formation. Among all velocity patterns, the most common pattern in shear layer and/or coaxial jet is the external excitation or forcing to enhance the mixing and combustion. There are many studies about forcing oscillations. Both vortex and entrainment is greatly enhanced in the forcing cases [3]. Forcing jet exit will greatly reduce the NOx, CO and soot emission of the lean premixed jet flame [4]. In the supersonic afterburning combustion, due to the difficulties of active control, a kind of cavity passive forcing is used to generate the large-scale vortex [5]. In these studies, the evolution of large-scale vortex from forcing oscillations plays an important role in combustion enhancement.

In both active and passive forcing jet problem, the maximum mixing or reaction production is always the concerning issues. The optimal St number is found at 0.25 in the axisymmetry coaxial air jet when taking entrainment into account [6]. In the bluff-body flame stabilizer, the optimal St is considered different at different equivalent ratio due to the preferred different flow structures [7]. Large scale vortex is found to enhance mixing and combustion in premixed afterburner at St=1 which matches the preferred mode of the hydrodynamic field in the near wake [8]. Although some articles have shown that there exists an optimal control to improve combustion performance. The effect of large-scale vortex formation by forcing on combustion is still unclear.

This paper focuses on the optimal characteristics of vortex evolution and combustion flow field structure under excitation. Two-dimensional coaxial oxyhydrogen-air mixture jets with the impulse oscillations chosen

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from $T = 20\mu s$, $40\mu s$, $60\mu s$ and $100\mu s$ is simulated, in order to find the optimal forcing oscillations and explain how excitation control influences vortex structure.

2 Numerical setup and mesh validation

Present paper simulates a two-dimensional coaxial fuel-air jet. Cold fuel issues from a center jet composed of 30% H_2 and 70% N_2 at 390K. The ambient air is 1400K at 1atm, which is high enough for H_2 to auto-ignite in the mixing layer. As in the scramjet engine, the jet velocity is far slower than the main air co-flow. Thus, the fuel jet velocity is at $1000m/s$ and air velocity is up to $2000m/s$. The convective velocity $U_c = 1549.5m/s$. The general setup description is presented in Fig.1.

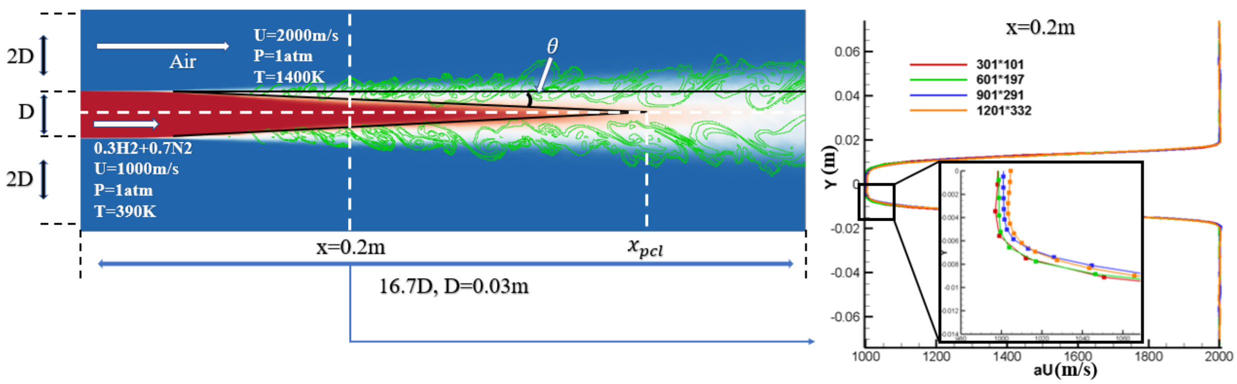

Figure 1: Numerical set up and mesh validation.

The simulations are implemented by in-house LES CFD code *ParNS3D*. The numerical validation for *ParNS3D* is present in [9]. The numerical simulation results of 2D shear layer are in good agreement with the experimental results. Four different meshes are used for grid independence validation. Non-forcing and noncombustible case is then simulated to check the convergence. The time average velocity component along stream wise direction at x=0.2m is chosen for comparison and the convergence of velocity component can be observed in Fig.1. The mesh with $901\times291\times2$ nodes is used for following calculations. In order to obtain a stable flow field, the flow field evolution is simulated without chemical reaction to 1ms (time step 1×10^{-8}s) in following calculations, then the chemical reaction mechanism is considered and chosen from Evans-Schexnayder model [10] and Jachimowski model [11] respectively. In the following study cases, in order to find the forcing effect on the general performance of mixing and combustion, the forcing impulse cycle is set at the fuel injection boundary. As shown in Fig.2, the impulse oscillations is chosen from $T = 20\mu s$, $40\mu s$, $60\mu s$ and $100\mu s$. When the fuel jet is at close status, the velocity at outflow is zero, which is shown as the blank area of Fig.2. The close status and the open status is both half oscillations $T/2$. In order to accurately calculate the amount of H_2 that has been ejected, the average flow mass rate is calculated as follows:

$$\overline{m}_{H_2} = \frac{1}{T}\int_0^T \int_{-y}^{y} \rho_{H_2} u dA dt \tag{1}$$

3 Results and discussion

3.1 Damkohler number

The length between the auto-ignition point and the injector is defined as the Lift-off height(short for LOH). The ignition point is defined as the point where temperature reaches 1500K and x coordinate is minimum. At the non-forcing cases that use Evans-Schexnayder model, the auto-ignition point is stabilized at approximately $x_{loh} = 0.04m$. Damkohler number (Da number) is defined as the characteristic time between flow and ignition $Da = \tau_h/\tau_r$. Here, the ignition delay time is $\tau_r = x_{loh}/U_c \approx 25.8\mu s$. As shown in Fig.1, the potential core length x_{pcl} of non-react cases is calculated from the mixing layer growth rate by the deviation angle θ, that is $x_{pcl} = D/2\theta \approx 0.6m$. Thus, the characteristic timescale for hydrodynamic can be defined as the $\tau_h = x_{pcl}/U_c$. Thus the Da number are calculated by two typical length scale [12]: $Da = \frac{x_{pcl}}{x_{loh}} \approx 17$. For cases that use Jachimowski model, the auto-ignition is faster as shown in Fig.3, which means smaller x_{loh}. At this Da number, it can find that combustion is mainly controlled by the mixing process, which explains the relative poor combustion performance at the no forcing case.

3.2 Comparison between different forcing oscillations

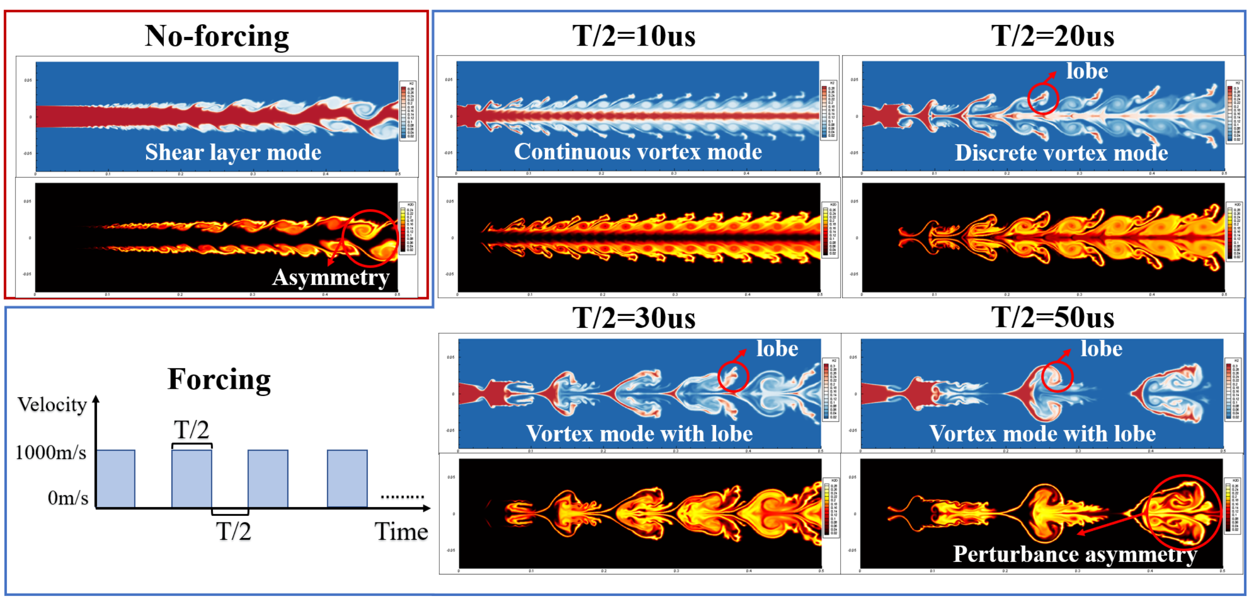

Figure 2: H2 mass fraction of non-react cases and water production of reacting cases at different forcing $T/2 = 10\mu s, 20\mu s, 30\mu s, 50\mu s$.

The general view of five different forcing cases that use Jachimowski model are compared in Fig.2. The non-forcing results shows the vortex layer at the far wake in reacting case. The mixing and combustion happen mainly at the mixing layer where Kelvin-Helmholtz instability makes the formation of vortex array. The vortex entrains the high speed hot air to mix the cold low speed fuel jet. Although fuel is ignited quickly, most of fuel can not be consumed along the streamwise due to poor mixing behavior.

Three flow structures modes are defined in Fig.2 to describe vortex feature, including shear layer mode and continuous vortex mode as well as vortex mode with lobe. Discrete vortex mode belongs to continuous vortex mode but the vortex is discrete. When forcing frequency is introduced, the flow is tend to the symmetry large scale vortex structures. As shown in Fig.2, the potential core length is greatly reduced. More air can be entrained into the fuel jet which makes the better performance of combustion. The impulse oscillation makes the vortex array more symmetry than that of non-forcing cases. However, the asymmetry behavior is shown again in $T/2 = 50\mu s$ case. The vortex size is also influenced by the forcing impulse oscillations. Moreover, the spacing between different vortex is larger as the impulse oscillations is longer. The similar phenomena can be found in cases that is simulated using Evans-Schexnayder model under the same inlet conditions.

The production of the reaction is the main target in the evaluation of the combustion. In order to objectively access the no forcing and forcing jet, normalized water production is recorded in reacting cases with/without forcing. The normalized production of water is defined as:

$$\overline{m}_{H_2O}(t) = \frac{\int_A \rho Y_{H_2O} dA}{\bar{\dot{m}}_{H_2} T} \tag{2}$$

T is the time period of the fuel jet is at open status. There shows the obvious increase of the normalized production of water at the forcing conditions in Fig.3. At $T/2 = 20\mu s$, The normalized production of water reaches the maximum comparing to other forcing cases. Although entrainment performance is influenced by the chemical reaction mechanism, but the evolution of vortex is similar. There exists an optimal forcing oscillation for both Evans-Schexnayder model and Jachimowski model. The relationship between ignition delay time and combustion enhancement needs to be discussed further in the future.

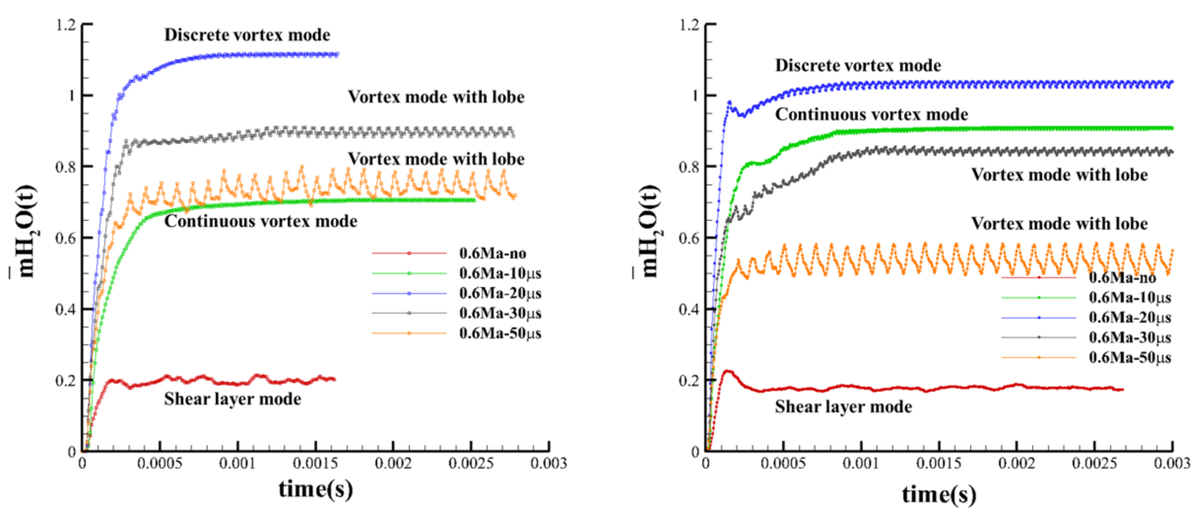

Figure 3: Left: Normalized production of water using Evans-Schexnayder model; right: Normalized production of water using Jachimowski model.

The results in Fig.2 and Fig.3 show that the limiting formation of vortex from each impulse forcing is found the cause of the superior behavior comparing to the no forcing jet. The vortex formation is influenced by the forcing impulse oscillations. The vortex structure changes from shear layer mode to vortex mode with lobe with forcing oscillations being larger. Discrete vortex mode which is the optimal vortex structure appears when forcing oscillations is $T/2 = 20\mu s$. Discrete vortex mode has best mixing and combustion performance because discrete vortex doesn't have "lobe" and evolves independently comparing to other vortex modes. More air is entrained into the fuel jet. Then, the vortex mode with lobe appears and reduces mixing and entrainment performance with the forcing oscillations becoming larger than $T/2 = 20\mu s$.

4 Conclusions

Forcing impulse cycle greatly improves combustion performance. The results in Fig.3 show that the maximum reaction production per unit mass of fuel of all forcing oscillations (from forcing period $T/2 = 20\mu s$ to $50\mu s$) is increased near six times than that of non-forcing case. The forced fuel injection is much more stable exhausted in short oscillations forcing ($T/2 < 30\mu s$). The limiting formation of vortex from each impulse forcing is found the reason why forcing case has superior behavior comparing to the no forcing case. Moreover, there exists a optimal forcing oscillations $T/2 = 20\mu s$ that makes the normalized production of water reach the maximum comparing to other forcing cases. Under high Da number condition, combustion is mainly controlled by equivalent mixing which is closely related to the continuous large-scale vortex flow structures. Three flow structures modes are defined in Fig.2 to describe vortex feature, including shear layer mode and continuous vortex mode as well as vortex mode with lobe. The vortex structure is influenced by the forcing impulse oscillations. Discrete vortex mode has best mixing and combustion performance because discrete vortex doesn't have "lobe" and evolves independently comparing to other vortex modes. Further experiments are needed to validate the optimal forcing oscillations.

5 Appendix

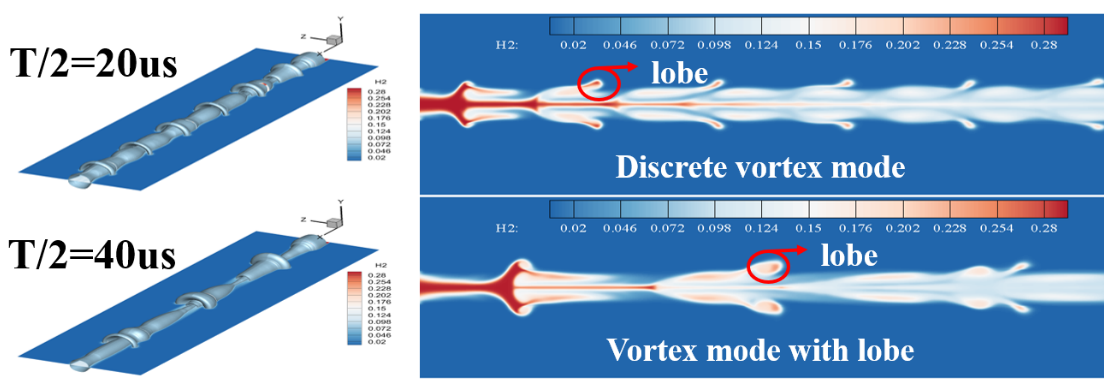

Figure 4: Up: H2 mass fraction of non-react cases at forcing $T/2 = 20\mu s$; Down: H2 mass fraction of non-react cases at forcing $T/2 = 40\mu s$.

Three dimensions simulations for $T/2 = 20\mu s$ and $T/2 = 40\mu s$ forcing cases without reaction are implemented here. The size of grid used for simulation is $601\times21\times27$ nodes. The vortex structure of 3D simulation results is different from that of 2D simulation results because of the stretch in z axis direction as shown in Fig.4. There is still some similarity between vortex structure of section results and 2D results. Discrete vortex mode and vortex mode with lobe can be observed in 3D simulation result. Besides, the optimal forcing phenomena can also be found in the experiment results [6–8]. Low speed forcing experiments are also implemented to study mixing characteristics [13]. Of course, more investigations into 3D effects on combustion with forcing oscillations will be done in the future, because conditions of experiments mentioned above are different from 2D cases in this paper.

6 Acknowledgement

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